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MECHANISMS OF INJURY IN MODERN LIGHTPLANE CRASHES: A STATISTICAL SUMMARY OF CAUSATIVE FACTORS

November 1962

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prepared by :

AVIATION CRASH INJURY RESEARCH
PHOENIX, ARIZONA
A DIVISION OF
FLIGHT SAFETY FOUNDATION, INC.
NEW YORK, NEW YORK

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FOR THE COMMANDER:

Kenneth B. Abel

KENNETH B. ABEL
Capt. USA
Adjutant

APPROVED BY:

William Nolan

WILLIAM J. NOLAN
USATRECOM Project Engineer

Task 9R95-20-001-01
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MECHANISMS OF INJURY IN MODERN LIGHTPLANE CRASHES: A STATISTICAL SUMMARY OF CAUSATIVE FACTORS

AvCIR 62-13

By

Richard G. Pearson, Ph. D.
Mildred H. Piazza

Prepared by
Aviation Crash Injury Research
A Division of
Flight Safety Foundation, Inc.
2871 Sky Harbor Blvd.
Phoenix, Arizona

for

U. S. ARMY TRANSPORTATION RESEARCH COMMAND
FORT EUSTIS, VIRGINIA

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ILLUSTRATIONS AND TABLES (cont'd.)

SUMMARY

This study was undertaken to evaluate the interrelationship between primary impact variables, seat and belt tiedown effectiveness, and injuries sustained by occupants of 342 lightplanes involved in spin-stall crashes or collisions with the ground while in flight. The data were obtained during the period 1953-1960 and are to be contrasted with data previously reported for the period 1942-1952 (when light aircraft were primarily of fabric-skin covering).

Contrary to the earlier findings, seat failure now occurs more frequently than belt failure. The curve of belt failure plotted as a function of impact velocity does not accelerate as rapidly as that from the earlier data, whereas the seat-failure curves from the two sets of data are comparable. Since injuries are found to be more severe when seats fail than when belts fail, there is a suggestion that seat tiedown improvements may not have kept pace with improvements in seat belt manufacture and installation. Overall, however, when tiedown is considered to be effective, injuries are less severe for the more recent data, thereby suggesting that better overall protection is afforded today's pilots. Occupants wearing shoulder harnesses were least severely injured, although some still received facial and skull fractures. Since structural collapse was generally not extensive for these data, flailing of the body against injury-producing structures within the occupant's environment is seen to be a significant source of injuries. Injury severity was found to increase little as a function of impact velocity, but did increase rapidly as a function of angle of impact.

CONCLUSIONS

1. The most critical determinant of injury and death in modern lightplane crashes is flailing of the body against injury-producing structures within the occupant's environment.

2. Injury severity in modern lightplane crashes is largely a function of severity of head injury.

3. When the tiedown chain remains intact, severity of injury is decreased even at high angles of impact and at impact velocities exceeding 90 miles per hour. Its value is further enhanced when the shoulder harness is used.

4. In general, better overall protection is afforded today's pilots, as witnessed by the fact that injuries are less severe for the recent data despite an average increase in velocities estimated at impact. This may be a reflection of aircraft design practices in addition to the increased rate at which overall tiedown is effective.

5. There is still room for improvement in the design, manufacture, and installation of components of the tiedown chain. It appears that seat tiedown improvements have not kept pace with improvements along other lines. There is a suggestion from the data that seats fail most often under conditions where vertical crash forces predominate.

RECOMMENDATIONS

1. Inasmuch as injury severity is so strongly related to severity of head injury, violent contact between the head and aircraft structures must be prevented. This can be done through use of the shoulder harness, of the crash helmet, and of crash-safe design principles within the cockpit.

2. Greater attention should be given to seat design and installation, especially with regard to incorporation of energy-absorption principles.

3. Hazards of the high-angle crash typical of the spin-stall crash need greater attention, together with further incorporation of crash safety design principles in aircraft structures.

4. A much better understanding of crash-injury dynamics may be realized if studies such as the present one were based upon larger numbers of cases known to be a random sample from the population of all accidents. The goal should be to obtain all accident injury cases. This would certainly facilitate the conduct of studies to determine the relation to injury severity of such factors as seated position, control wheel or landing gear characteristics, high wing versus low wing, single versus twin engine, etc.

INTRODUCTION

From individual accident case analyses made over the last 20 years, there has emerged a general picture of the cause of most injuries in lightplane crashes. Injuries were not to be attributed to primary crash forces *per se* but rather to factors that were indirectly a function of such forces, principally structural collapse, tiedown failure, and flailing of the head and extremities against injury-producing structures within the occupant's environment. But lacking from this work was knowledge of more precise relationships between the variables at impact, structural damage, tiedown chain effectiveness, and injury severity. Statistical studies of such relationships that could ultimately yield suitable recommendations for the design engineer became feasible about two years ago when a capability for automatic data processing was supported by the National Institutes of Health and the Transportation Research Command, U. S. Army.

The first in a series of studies conducted under this support revealed both damage to occupiable structures and injury severity to correlate less with primary impact variables (e.g., velocity, angle of impact, deceleration distance) than they did with each other (reference 1). A need to take into account the role of tiedown effectiveness was apparent; consequently, a second study was undertaken. With structural collapse controlled, the results indicated that factors other than tiedown failure were responsible for the major portion of injury severity, although, to be sure, tiedown failure did contribute significantly to injury (reference 6). Hence, a third study was conducted in which attention was focused more closely on not only degree of injury but also area of injury and how these are related to impact conditions for a group of occupants whose tiedown did not fail (reference 5). The principal conclusion of this study was that crucial injuries--those to the skull and its contents, the cervical spine, and the upper torso--largely stem from flailing of the body against injury-producing structures within the occupant's environment.

Now, it should be pointed out that all of the above studies were based on data collected during the period 1942-1952. Eighty percent of the aircraft included in these data were of fabric-skin covering. The study to be described herein will provide comparison figures[1], based on more

[1] To the extent that there have been changes in old biases or introduction of new ones in the investigation of crashes, in sampling, or in coding of crash data (e.g., due to training, redesign of report forms, etc.) over the time span covered, such comparisons might be considered invalid. However, on the basis of conferences with persons who have been involved with AvCIR projects since 1942, the authors feel that such factors can be minimized.

recent data collected from 1953 to 1960, by which previous findings can be accepted or rejected. It will be interesting to see if injury statistics differ with this sample in which all-metal aircraft predominate. Impact velocities will be higher, but perhaps the injury statistics will reveal this fact to be offset by sturdier construction, design changes, and incorporation of safety measures. Hopefully, the results of this study will help us attain the goal of better understanding the determinants of injury severity in lightplane crashes.

CHARACTERISTICS OF THE ACCIDENT POPULATION

A total of 623 occupants was involved in 342 accidents included in this study for analysis. There were 19 different makes of aircraft ranging in weight from 850 to 9,000 pounds and in occupant capacity from one to ten. Table 1 gives the number and percentage of cases included in the study for various types of accidents. Data from accidents in which the aircraft burned, crashed inverted, or cartwheeled after impact were not used. It is important to note that the data collection system arbitrarily excluded the reporting not only of incidents but also of crashes termed "nonsurvivable" due to focusing of interests on problems of reducing injuries through safety design practices. (A nonsurvivable crash is defined as one in which structural collapse of the occupiable area is so extensive as to preclude occupant survivability.) Because of the above restrictions, the data cannot be construed as a sample, random or stratified, from the parent population of all accident events and should not be used to provide estimates of population values. The data to be presented are to be viewed with this qualification in mind. In retrospect, however, the need is seen for obtaining data on incidents and on "nonsurvivable" as well as "survivable" crashes in order that a completed picture yielding knowledge of force transmission could then be deducible by the engineer having structural design specifications in his hands.

TABLE 1
NUMBERS AND PERCENT OF VARIOUS TYPES OF ACCIDENTS INCLUDED IN THE ACCIDENT POPULATION

Type of Accident	Number	Percent
Landing	24	7.0
Forced landing	74	21.6
Take-off	5	1.5
Spin-stall	85	24.9
Collision with object	99	28.9
Collision with ground	42	12.3
Other	13	3.8
	342	100.0

RESULTS

Reported injuries for the above cases had previously been coded by analysts according to type, severity, and body area. Ten areas of injury were considered relevant to the analyses. In general, concern was focused upon fractures, dislocations, intracranial lesions, and internal injuries--the types of injuries felt to be reasonable reflections of the crash picture. Injury severity was determined from the AvCIR Scale of Injury, whose values range from 1, essentially uninjured, to 10, fatal lesions in three or more areas of the body. Scale values 7-10 represent injuries with fatal consequences, higher values necessarily reflecting more severe trauma. Computed mean degree-of-injury (hereafter, MDI) values provide a way to compare the effects of different crash conditions (e.g., high versus low impact velocity).

OVERALL PICTURE OF TIEDOWN EFFECTIVENESS

Analysis of the data began with a look at the role played by tiedown chain conditions in causing or preventing injury. Here the seat, seat belt, and shoulder harness data for each of 623 occupants were considered. It should be noted that since a crash is represented each time one of its occupants is included in the total of 623, the results obtained are not statistically independent. That is, conclusions regarding the degree of relationship between impact variables and either tiedown effectiveness or sustained injuries are not in order.

Excluded from consideration in this analysis were cases involving collapse of major structures adjacent to an occupant's seat and in which there was evidence of impact upon the front seat from rear-seated occupants. This was done to control for conditions likely to cause injuries beyond those attributable to tiedown failure.

The subgroups constituted for comparison, and which appear as column headings in Table 2, were delimited as follows: "Harness Held" includes 55 cases in which both shoulder harness and seat belt were used and held, and the seat was intact, distorted, or collapsed but its fastenings were intact; "Seat and Belt Held" includes 426 cases which met the same criteria except that the shoulder harness was either not installed or not used; "Seat Failed" includes 77 cases in which the occupant's seat was partly or completely torn free from its area of attachment; "Belt Failed" includes 50 cases in which the seat was intact, distorted, or collapsed but its fastenings were intact, and either the belt webbing was broken or torn, the buckle failed or slipped, or the belt anchorage failed; included in the "Belt Not Used"

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TABLE 2

RELATION OF TIEDOWN EFFECTIVENESS TO DEGREE OF INJURY

		Harness, Seat, and Belt Tiedown Effectiveness						
		1. Harness Held	2. Seat and Belt Held	3. Seat Failed	4. Belt Failed	5. Belt Not Used	6. Thrown from Aircraft	7. All Occupants
Number of Observations		55	426	77	50	15	(15)	623
Percentage of Total		8.8	68.4	12.4	8.0	2.4	(2.4)	
	10. Fatal	2*	1	1	2	7	7	1
	9. Fatal	0	3	8	8	7	0	4
	8. Fatal	2	1	1	0	0	0	1
Degree	7. Fatal	2	6	9	10	13	13	6
of	6. Critical	7	7	13	10	7	0	8
Injury	5. Serious	11	10	16	8	7	20	10
	4. Severe	15	14	27	28	0	7	16
	3. Moderate	7	14	6	4	0	0	11
	2. Minor	18	18	16	14	27	27	18
	1. Uninjured	36	28	3	16	33	27	25
Mean Degree of Injury		2.96	3.32	4.75	4.30	3.80	3.67	3.56

*Values indicate percentage of total number of occupants within column receiving specified degree of injury.

category are 15 occupants who were known not to have their belts fastened at the time their plane crashed. Of all those occupants whose belt or seat failed or who did not use a belt, 15 were thrown out of the aircraft at or after impact; data on these cases, which are also included in columns 3, 4, and 5, are presented for comparison only and appear in column 6, "Thrown from Aircraft".

What was immediately apparent from first glance at the data of Table 2 was the encouraging finding that MDI was significantly less for the modern data, as compared to the 1942-1952 data (reference 6), over all subgroups. Approximately nine percent of the occupants used a shoulder harness, whereas only one percent of those from the earlier data used a harness. Those wearing a harness were least severely injured; in fact, 36 percent escaped injury altogether. Compare this figure with a 3 percent value for those whose seat failed and a 16 percent value for those whose belt failed. In agreement with the earlier data, MDI for those whose belt failed was less than that for those whose seat failed. Cumulating percentages for the fatal degrees of injury within each subgroup, one will obtain the following fatality rates: harness effective, 6 percent; seat and belt effective, 11 percent; seat failed, 19 percent; belt failed, 20 percent; belt not used, 27 percent; and thrown from aircraft, 20 percent.

Contrary to the earlier findings, seat failure occurred more frequently than belt failure. Belt failures represented only 8 percent of the recent cases as contrasted with 22 percent of the earlier cases. Seat failures actually increased! They represent 12.4 percent of the recent data as contrasted with only 9 percent of the earlier data. But overall, there was an increase in the percentage of cases in which tiedown could be considered effective--from 67 percent for the 1942-1952 data to 77.2 percent for the 1953-1960 data. Fifteen occupants, 2.4 percent of the total, did not make use of their seat belt--a small decrease from the rate of 4.2 percent found previously. Of those 142 occupants experiencing tiedown failure or not using seat belts, 15 (or 10.6 percent) were thrown out of the aircraft--a decrease from the rate of 17.3 percent found in the earlier data.

As regards area of body injured (Table 3), skull and facial fractures, extremity fractures or dislocations, and intracranial or intrathoracic lesions occurred, as one would expect, considerably more often when tiedown was considered ineffective. Particularly prominent were the following statistics: Brain injuries were sustained by 45 percent of those occupants whose seat failed and by 36 percent of those whose belt failed. Head area injuries were sustained by occupants using a

TABLE 3

RELATION OF TIEDOWN EFFECTIVENESS TO AREA OF INJURY

		Harness, Seat, and Belt Tiedown Effectiveness						
		1. Harness Held	2. Seat and Belt Held	3. Seat Failed	4. Belt Failed	5. Belt Not Used	6. Thrown From Aircraft	7. All Occupants
Number of Observations		55	426	77	50	15	(15)	623
	Skull	11*	8	17	26	27	13	11
	Brain	24	22	45	36	33	27	26
	Facial	9	13	17	16	7	7	13
Area	Cervical Spine	4	4	5	8	7	7	5
of	Upper Torso	11	15	30	22	20	13	17
Injury	Thoracic Spine	7	4	3	4	0	7	4
	Lower Torso	4	4	6	0	0	0	4
	Lumbar Spine	11	11	19	10	7	13	12
	Upper Extremities	11	9	19	24	13	13	12
	Lower Extremities	25	22	40	44	13	13	26

* Values indicate percentage of total number of occupants within column receiving injuries in specified area.

shoulder harness, but apparently the severity was less than for those not using a harness. In agreement with previous findings, lumbar spine, lower-extremity and upper-torso injuries are observed to occur in significant numbers when seats tear free. Lumbar spine fractures are noticeably fewer when belts are not worn--another confirmation of an earlier finding. The data for cervical spine, thoracic spine, and lower torso injuries were not substantial and thus do not occasion a discussion.

THE ROLE OF IMPACT VARIABLES

In order to define the role played by impact conditions in the picture presented so far, an evaluation was made of tiedown effectiveness as a function of the following variables: (1) estimated velocity at principal impact; (2) estimated angle between the flight path of the aircraft and the slope of the terrain at principal impact; (3) horizontal stopping distance as determined from gouge measurement, resting position of the aircraft, and structural collapse.

Impact Velocity

The relation of tiedown effectiveness to sustained injuries as a function of impact velocity is presented in Table 4. Within each velocity category, the percentage of observations falling within the three tiedown effectiveness categories (abbreviated BH, SF, and BF for Both Held, Seat Failed, and Belt Failed, respectively) has been determined and then plotted in Figure 1. For this and the remaining figures[2], the shoulder harness cases have been merged with those in which both seat and belt were effective; also, the few cases in which belts were not used are not plotted. The curve of belt failure in Figure 1 was not found to accelerate as rapidly as that from the 1942-1952 data, whereas the seat failure curves from the two sets of data are comparable. As in the earlier period, tiedown is still effective over 70 percent of the time at impact velocities exceeding 90 miles per hour.

The MDI data are plotted in Figure 2. Although one cannot place much faith in the veracity of the belt-failure and seat-failure curves since they are based upon small subgroup frequencies, there is certainly an indication that injury severity does increase as a function of impact velocity. The linear plot of the data for those occupants whose tiedown did not fail should be noted with interest. It is encouraging to find

[2] The reader is cautioned against interpreting statistics based upon small subgroup frequencies.

TABLE 4
RELATION OF TIEDOWN EFFECTIVENESS TO SUSTAINED INJURIES AS A FUNCTION OF IMPACT VELOCITY

Seat and Belt Condition		30 - 39 BH	30 - 39 SF	30 - 39 BF	40 - 49 BH	40 - 49 SF	40 - 49 BF	50 - 59 BH	50 - 59 SF	50 - 59 BF	60 - 69 BH	60 - 69 SF	60 - 69 BF	70 - 89 BH	70 - 89 SF	70 - 89 BF	90-Over BH	90-Over SF	90-Over BF
	No. Observations	70	6	7	79	12	15	113	18	8	89	12	7	52	12	5	42	11	6
a. Degree	% Fatal	6	17	0	8	8	13	10	22	0	11	8	57	13	8	20	14	36	50
of	% Uninjured	39	0	14	33	8	0	29	6	62	31	0	0	29	0	0	14	0	0
Injury	Total		83			106			139			108			69			59	
	Skull	4*	17	14	8	8	27	6	17	0	6	17	43	13	8	60	7	18	33
	Brain	17	33	0	22	25	53	22	44	12	16	25	43	27	50	60	26	73	50
b.	Facial	10	17	14	10	17	20	11	28	0	12	17	0	13	8	60	24	9	17
	Cervical Spine	6	0	0	3	0	0	4	6	0	6	0	43	8	0	0	0	27	17
Area	Upper Torso	14	33	0	10	17	33	16	39	0	10	17	14	17	33	80	24	55	50
of	Thoracic Spine	1	0	0	4	0	7	4	6	12	7	8	0	8	0	20	2	0	0
Injury	Lower Torso	3	0	0	0	8	0	5	6	0	4	0	0	4	17	0	5	9	0
	Lumbar Spine	3	17	0	5	0	7	10	11	0	15	17	14	17	25	40	10	18	17
	Upper Extremities	7	33	0	4	8	27	14	39	0	4	0	43	12	17	60	19	27	17
	Lower Extremities	17	33	14	20	25	60	20	39	12	17	42	43	27	67	100	29	36	50

Impact Velocity (MPH) spans all velocity columns.

*Values indicate percentage of total number of occupants within column receiving injuries in specified area.

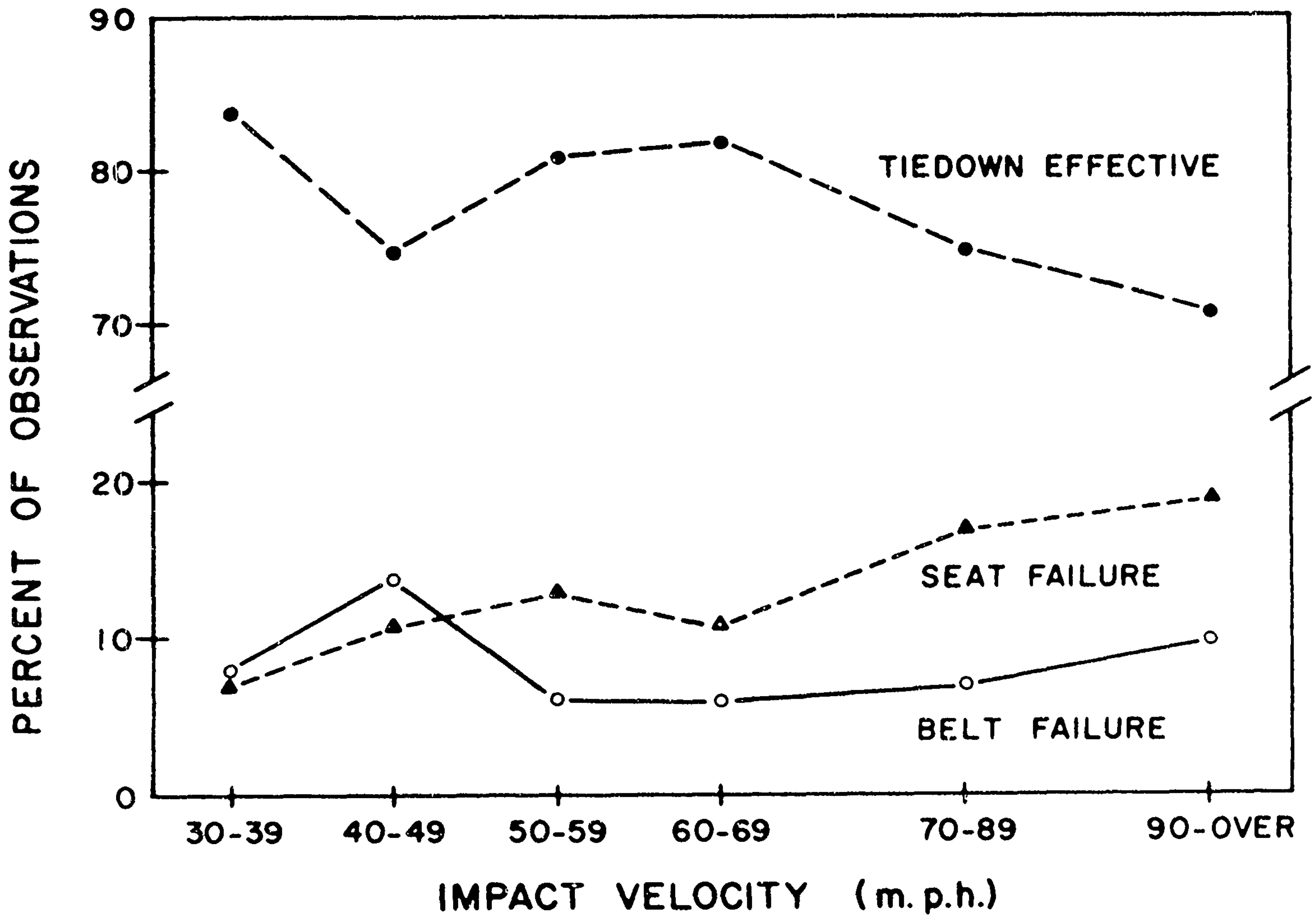

Figure 1. Relation of Tiedown Effectiveness to Impact Velocity.

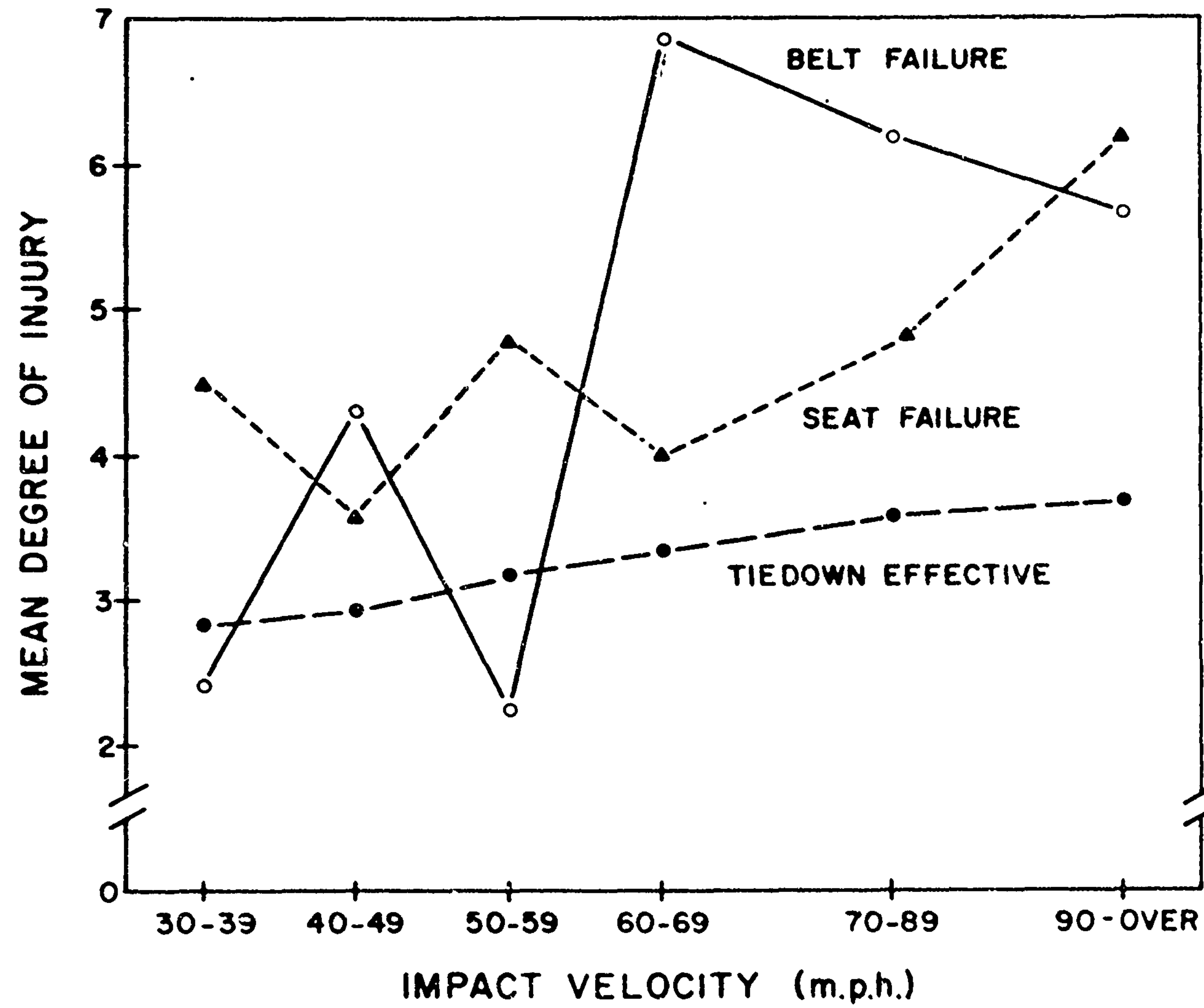

Figure 2. Relation of Injury Severity to Impact Velocity.

tiedown to be so effective in reducing injury: With effective tiedown, injury severity increases little as a function of impact velocity! If this linear plot were extended, it would not reach the fatal level of injury (seventh degree) until approximately a 300-mile-per-hour impact velocity had been attained. However, there is reason to doubt that the plotted points at higher velocities are representative of the injury severity that could be expected due to the fact that nonsurvivable crashes were not involved in the analyses. A positively accelerated increasing curve would seem to be more reasonable in this instance.

The value of effective tiedown is further documented by reference to the last three columns of Table 4. At impact velocities exceeding 90 miles per hour, half of those occupants whose belt failed, 36 percent of those whose seat failed, but only 14 percent of the group whose tiedown remained effective sustained fatal injuries. Note further that 14 percent of the latter group escaped <u>without</u> injury. Also revealing are the skull, brain, and upper torso values for the same columns.

Angle of Impact

Figure 3 shows tiedown effectiveness plotted as a function of impact angle. The one point worth noting here is the <u>increase</u> in overall tiedown effectiveness at high angles, as contrasted with moderate angles. This finding was observed in the earlier data (reference 6) and appears to be related to a decline in the rate of seat failures at high angles. However, small subgroup frequencies preclude strong statements concerning the two failure curves.

The value of effective tiedown in preventing injury, even at the higher impact angles, is once more demonstrated in Figure 4. When seats do fail at the higher angles, note that MDI approaches the fatal level. By contrast, as seen in Table 5, 52 percent of those occupants whose tiedowns were considered effective escaped injury altogether in low-angle crashes. Irrespective of tiedown effectiveness, MDI is clearly seen to increase rapidly as a function of impact angle. Particularly critical at the higher angles were brain injuries; these are found in 75 percent of the seat-failure cases, 57 percent of the belt-failure cases, and even 45 percent of the cases where tiedown was effective.

Stopping Distance

The value of a long deceleration distance is seen clearly in Figure 5; at distances exceeding 225 feet, tiedown failure was not to be observed.

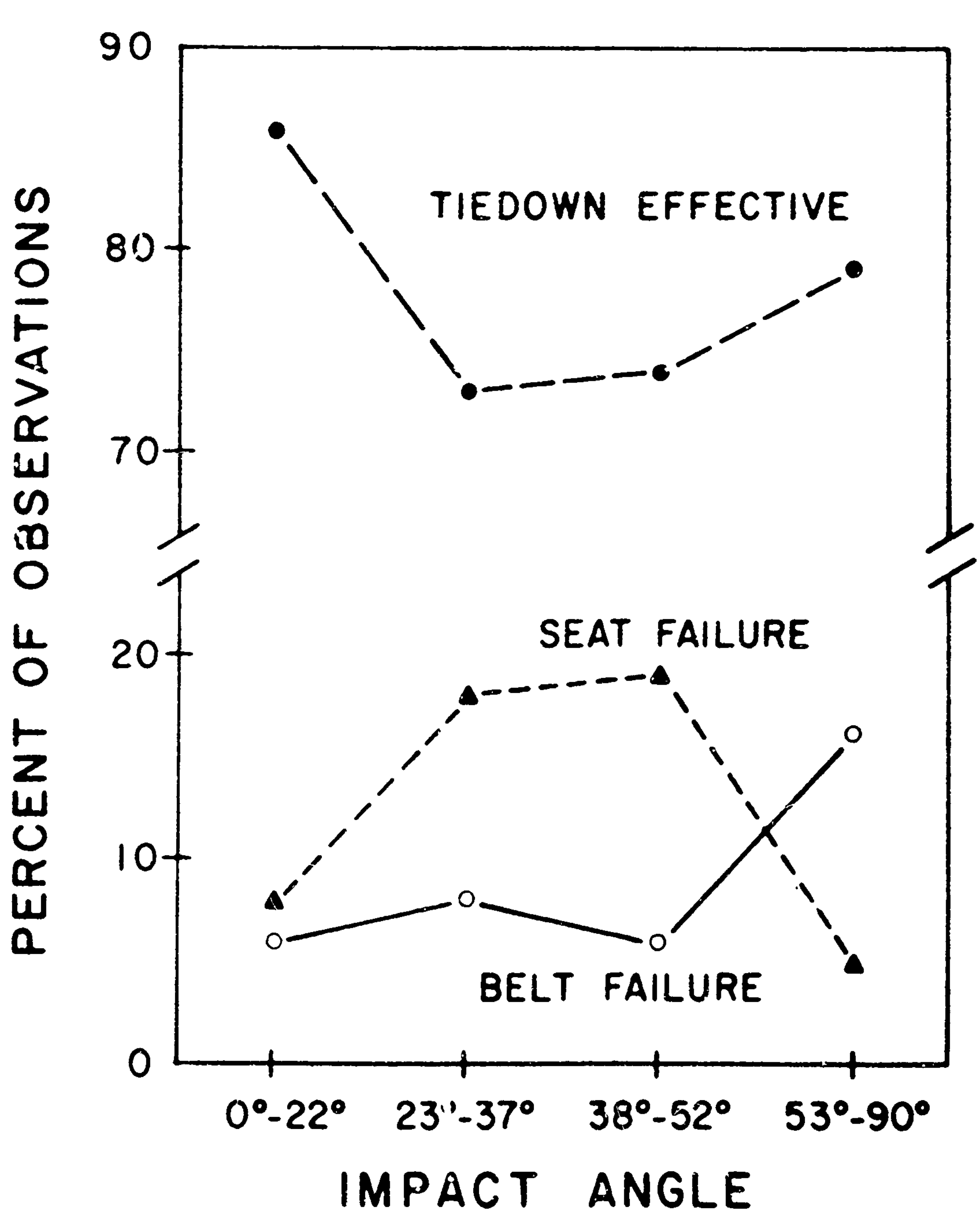

Figure 3. Relation of Tiedown Effectiveness to Angle of Impact.

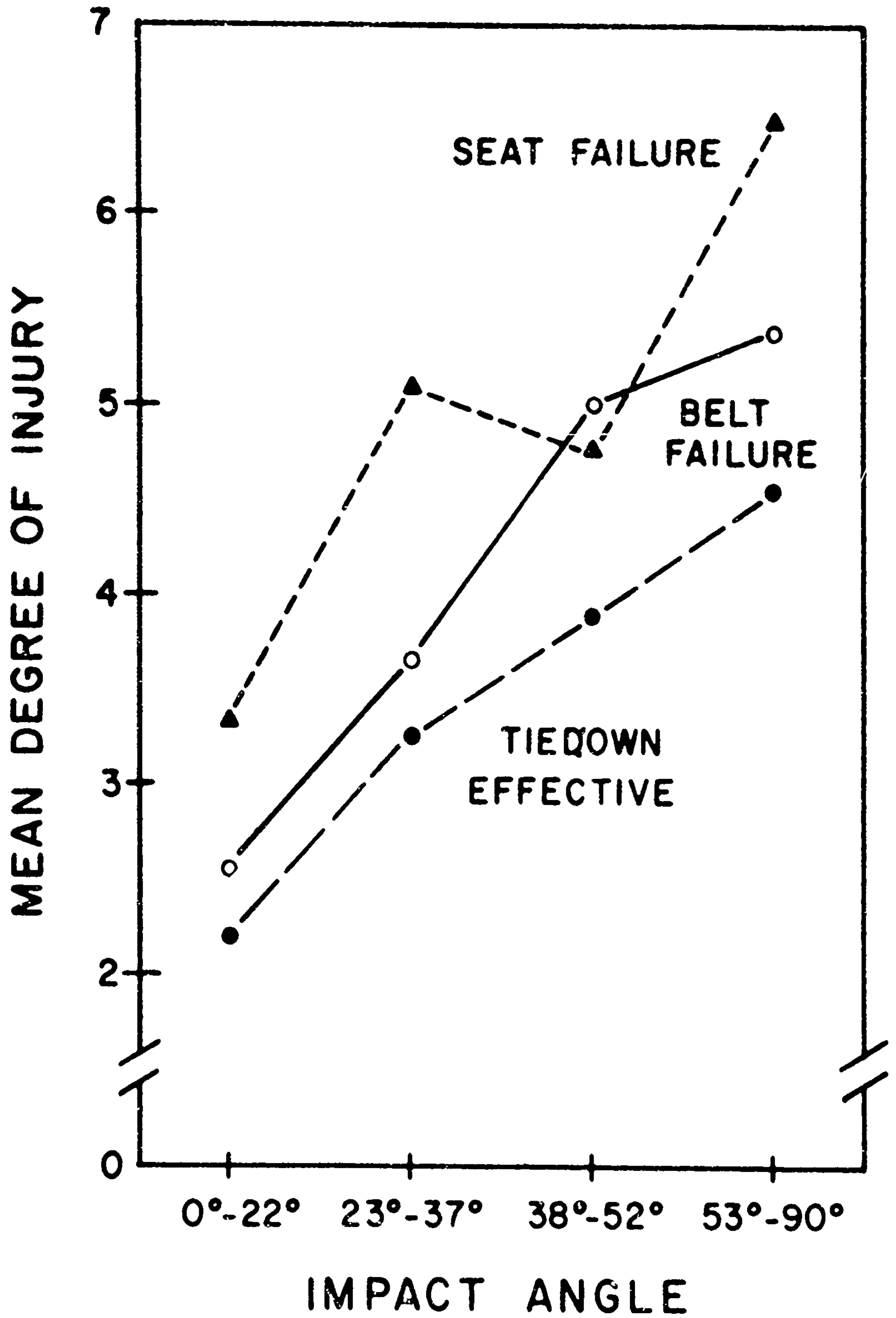

Figure 4. Relation of Injury Severity to Angle of Impact.

TABLE 5

RELATION OF TIEDOWN EFFECTIVENESS TO SUSTAINED INJURIES AS A FUNCTION OF ANGLE OF IMPACT

		Angle of Impact											
		0° - 22°			23° - 37°			38° - 52°			53° - 90°		
Seat and Belt Condition		BH	SF	BF	BH	SF	BF	BH	SF	BF	BH	SF	BF
a.	No. Observations	126	11	9	108	27	12	92	24	8	69	4	14
Degree	% Fatal	4	9	11	6	26	0	16	17	25	20	25	29
of	% Uninjured	52	9	44	24	0	17	21	4	0	12	0	0
Injury	Total		146			147			124			87	
	Skull	2*	0	22	10	22	8	14	17	38	10	25	43
	Brain	7	9	22	26	48	17	25	46	62	45	75	57
b.	Facial	4	9	11	12	11	17	12	17	12	25	50	29
	Cervical Spine	2	18	0	2	7	0	7	0	12	9	25	14
Area of	Upper Torso	4	27	11	17	22	25	15	38	0	29	25	30
Injury	Thoracic Spine	3	9	11	3	4	8	5	0	0	3	0	0
	Lower Torso	0	0	0	5	7	0	4	12	0	7	0	0
	Lumbar Spine	8	9	11	17	22	25	11	17	0	7	25	7
	Upper Extremities	2	0	11	4	22	8	12	17	38	23	75	36
	Lower Extremities	13	36	22	16	41	50	27	42	38	46	75	57

*Values indicate percentage of total number of occupants within column receiving injuries in specified area.

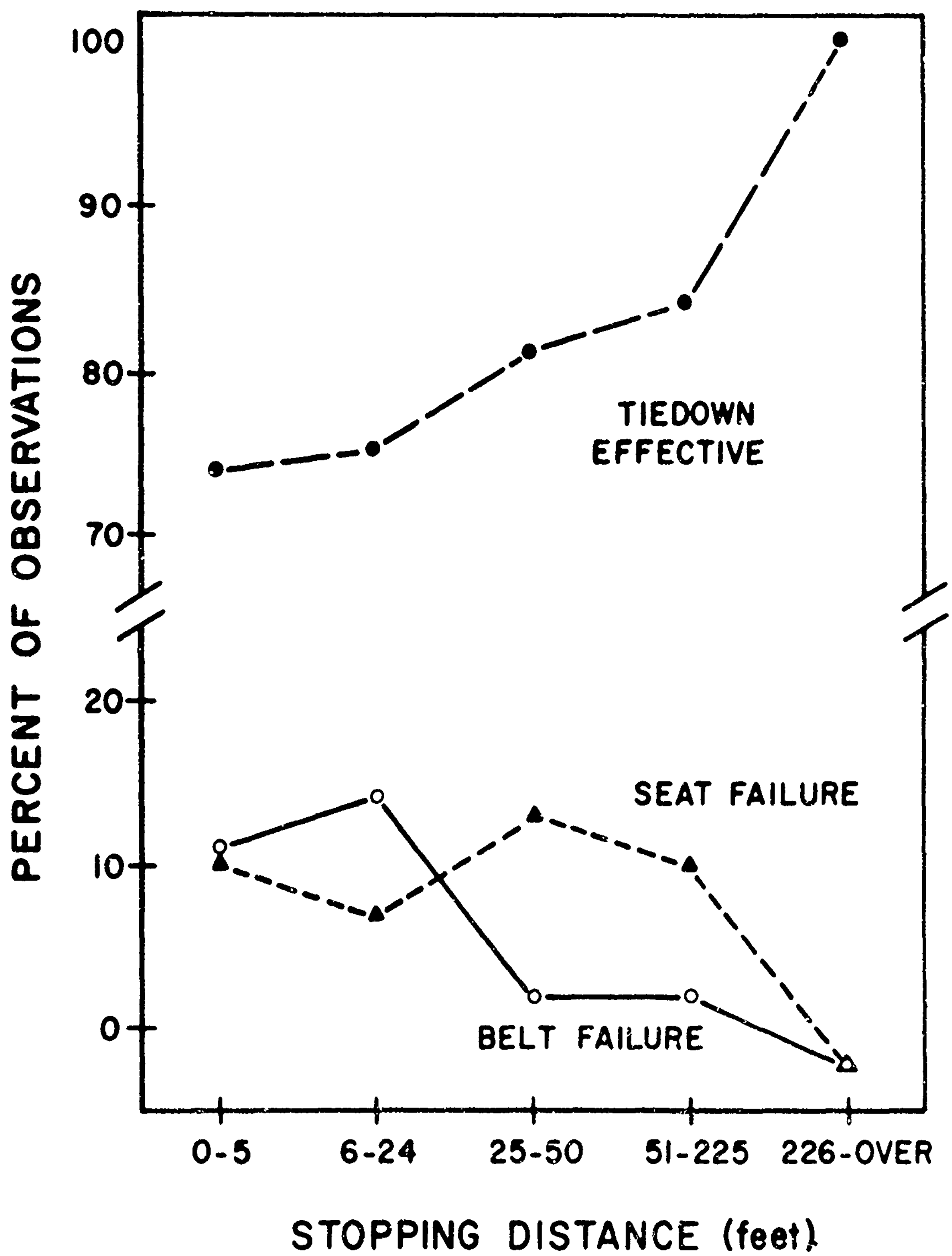

Figure 5. Relation of Tiedown Effectiveness to Stopping Distance.

As observed in Table 6, there were 22 occupants in this subgroup; exactly half of these escaped injury, while the other 11 sustained only facial bone and extremity fractures. Existence of U-shaped relationships between stopping distance and seat and belt failures suggested by earlier data (reference 6) is not supported by the data plotted in Figure 5.

Figure 6 presents the MDI data; note how important it is for seats not to tear free if the occupant is to survive a long deceleration without serious injury. On the other hand, effective tiedown begins to lose its importance as a factor in reducing injury at extremely short deceleration distances.

Whereas the comparable MDI curves from the 1942-1952 data were all U-shaped (reference 6), only one of the three curves of Figure 6 here is U-shaped; and the basis of even this curve is weak, being based on small subgroup frequencies.

THE ROLE OF STRUCTURAL COLLAPSE

Having studied the relation of tiedown failure to injury severity, another approach to evaluating the accident cases was considered. Going back to the case files on the 342 accidents included in the above analyses, a sample of 268 was selected that included pilots only[3] and only those cases in which tiedown was effective, i.e., seat and belt failure were not in evidence. The question to be asked then is: What caused the injuries to these pilots when tiedown failure is not a contributing factor?

Tables 7, 8, and 9 present the injury statistics as related to the three primary impact variables. By comparing the values seen there with those for the "BH" (Both Held) columns of Tables 4, 5, and 6, one can make a determination as to whether being the pilot, rather than a passenger, makes any difference in terms of injuries. A little less than half of those persons included in the data discussed in the previous section were passengers. Tiedown failure actually occurred more frequently in the case of the 281 passengers (24.2 percent) than with the 342 pilots (21.6 percent). Yet, with tiedown considered effective, one will find that, overall, the injury severity figures of Tables 7-9 are higher than those to be compared from the previous section. Pilots

[3] Statistics presented in this section can, therefore, be treated as statistically independent. This permits one to determine the degree of relationship between two variables.

TABLE 6

RELATION OF TIEDOWN EFFECTIVENESS TO SUSTAINED INJURIES AS A FUNCTION OF STOPPING DISTANCE

		Stopping Distance														
		Extreme 0' - 5'			Short 6' - 24'			Moderate 25' - 50'			Long 51' - 225'			Ext. Long 226' - Over		
Seat and Belt Condition		BH	SF	BF	BH	SF	BF	BH	SF	BF	BH	SF	BF	BH	SF	BF
a. Degree of Injury	No. Observations	84	14	15	71	9	15	111	21	5	168	24	8	22	0	0
	% Fatals	26	29	33	10	22	20	9	10	20	5	17	12	0	0	0
	% Uninjured	12	7	0	11	0	7	35	0	40	34	0	12	50	0	0
	Total		113			95			137			200			22	
b. Area of Injury	Skull	18*	21	47	7	11	20	8	14	20	5	17	38	0	0	0
	Brain	40	43	60	25	56	27	21	48	40	17	46	38	0	0	0
	Facial	24	14	20	13	33	20	10	14	0	10	17	25	9	0	0
	Cervical Spine	6	0	20	7	0	0	3	5	20	1	12	0	0	0	0
	Upper Torso	25	50	53	20	33	13	15	24	0	11	25	0	0	0	0
	Thoracic Spine	4	0	7	3	0	0	5	0	20	5	4	12	0	0	0
	Lower Torso	10	7	0	3	0	0	2	10	0	2	4	0	0	0	0
	Lumbar Spine	6	7	13	10	11	7	16	33	0	10	8	25	0	0	0
	Upper Extremities	19	21	33	15	33	20	5	19	0	5	8	12	9	0	0
	Lower Extremities	46	43	67	17	44	33	19	38	20	18	38	50	5	0	0

* Values indicate percentage of total number of occupants within column receiving injuries in specified area.

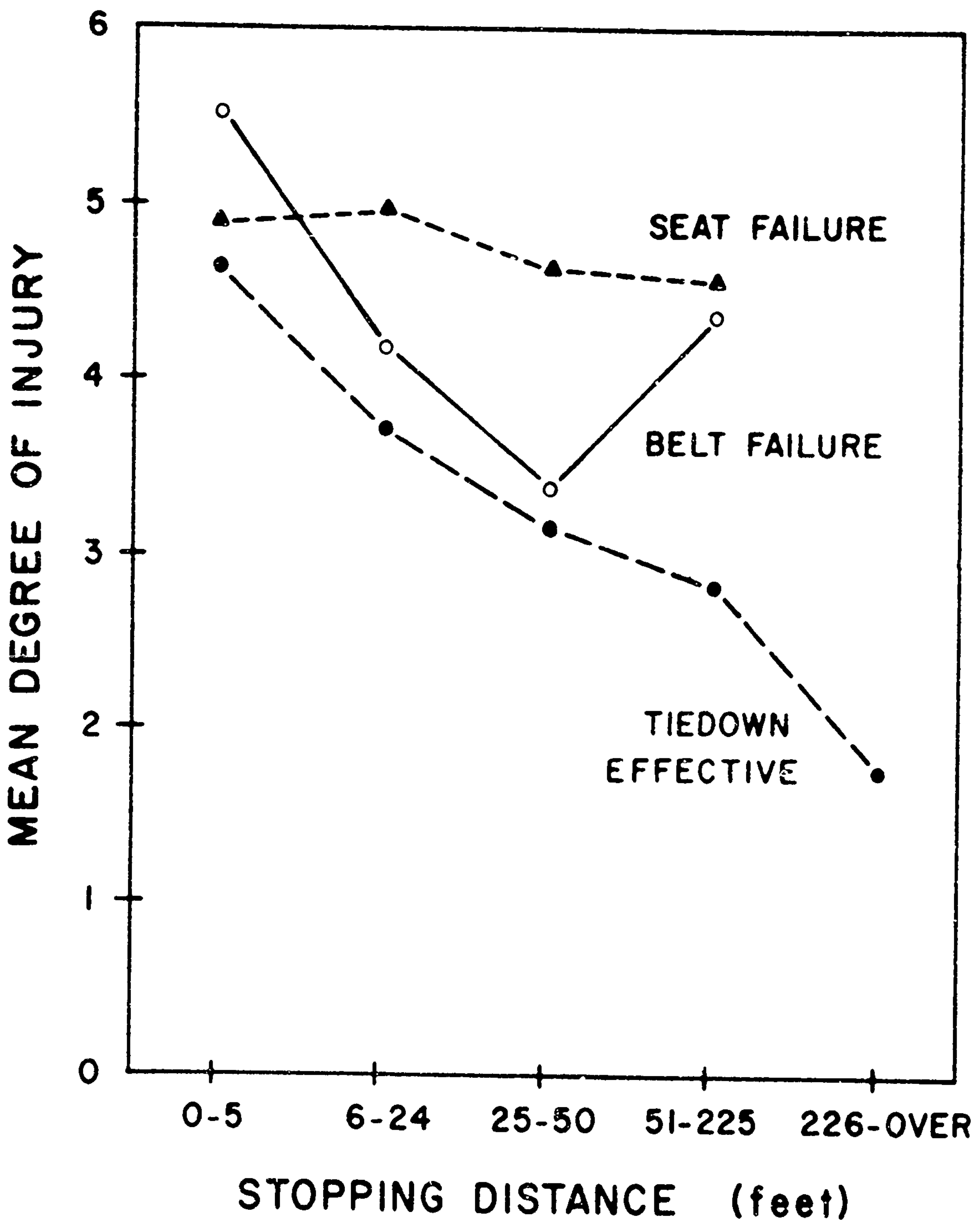

Figure 6. Relation of Injury Severity to Stopping Distance.

TABLE 7

RELATION OF SUSTAINED INJURY TO IMPACT VELOCITY

		Impact Velocity (MPH)					
		30 - 39	40 - 49	50 - 59	60 - 69	70 - 89	90 - Over
a. Degree of Injury	No. Observations	45	48	58	48	31	16
	% Fatal	11	8	12	15	16	19
	% Uninjured	31	31	21	25	19	25
	Mean	3.31	3.17	3.52	3.54	3.90	3.62
b. Area of Injury	Skull	9*	8	9	10	16	12
	Brain	22	23	34	19	29	31
	Facial	16	15	23	17	19	31
	Cervical Spine	7	4	6	8	10	0
	Upper Torso	18	23	21	19	23	25
	Thoracic Spine	2	6	0	4	10	0
	Lower Torso	4	0	8	2	6	0
	Lumbar Spine	4	4	12	4	13	12
	Upper Extremities	13	4	21	6	10	6
	Lower Extremities	24	23	31	27	32	31

*Values indicate percentage of total number of occupants within column receiving injuries in specified area.

TABLE 8
RELATION OF SUSTAINED INJURY TO ANGLE OF IMPACT

		Angle of Impact			
		0° - 22°	23° - 37°	38° - 52°	53° - 90°
a. Degree of Injury	No. Observations	66	63	48	47
	% Fatal	11	10	17	19
	% Uninjured	47	21	17	11
	Mean	2.53	3.63	4.04	4.66
b. Area of Injury	Skull	6*	16	15	11
	Brain	15	32	29	47
	Facial	5	17	19	38
	Cervical Spine	3	3	15	6
	Upper Torso	6	21	21	34
	Thoracic Spine	2	5	4	2
	Lower Torso	0	3	6	6
	Lumbar Spine	3	13	8	9
	Upper Extremities	3	3	15	28
	Lower Extremities	17	22	29	60

*Values indicate percentage of total number of occupants within column receiving injuries in specified area.

TABLE 9

RELATION OF SUSTAINED INJURY TO STOPPING DISTANCE

		Stopping Distance				
		Extreme 0' - 5'	Short 6' - 24'	Moderate 25' - 50'	Long 51' - 225'	Ext. Long 225' - Over
a.	No. Observations	59	45	68	78	8
	% Fatal	29	7	12	9	0
Degree of	% Uninjured	10	11	31	32	50
Injury	Mean	4.81	3.75	3.38	2.94	1.75
	Skull	20*	7	12	6	0
	Brain	41	29	26	22	0
	Facial	31	22	16	9	25
b.	Cervical Spine	5	9	4	3	0
	Upper Torso	29	24	19	15	0
Area of	Thoracic Spine	3	4	4	3	0
Injury	Lower Torso	12	2	0	1	0
	Lumbar Spine	8	7	12	5	0
	Upper Extremities	22	18	6	5	0
	Lower Extremities	51	29	24	18	12

*Values indicate percentage of total number of occupants within column receiving injuries in specified area.

are more severely injured than their passengers. This may be because pilots are normally seated in a position where injuries could be attributed to collapse of forward structures and/or to forceful contact with the controls or panel (of course, this argument would not apply in the case where a passenger was seated behind a dual control wheel).

But there should be no question that today's pilots are better protected from injury. Injuries are considerably less severe for the more recent data--and this despite an average increase in velocities estimated at impact! One can determine this by comparing the data of Tables 7-9 with earlier data (reference 5, Tables 1-3). Although the earlier data were based on only those cases involving the occupant sitting in the left front seat (normally the pilot), they should suffice for comparison. For example, MDI for impact velocities over 70 miles per hour was 6.46 for the 1942-1952 data, while for the recent data MDI was 3.90 for impact velocities between 70 and 90 miles per hour and 3.62 for velocities exceeding 90 miles per hour. For angle of impact, compare MDI of 4.66 over the 53° - 90° range for the 1953-1960 data with those of 5.53, 5.69, and 6.04 over the ranges 31° - 45°, 46° - 60°, and 61° - 90°, respectively, for the earlier data.

Notwithstanding the evidence for better protection and the fact that tiedown was considered effective in the cases represented in Tables 7-9, considerable injury is still apparent. Scanning the data makes obvious the fact that high-angle, short-deceleration crashes account for a greater proportion of injury severity. But what of other determinants of trauma? Perhaps structural collapse is a critical factor. Data on the relation of injury severity to damage to the pilot's physical environment, as shown in Table 10, do not appear to support this view, however. In only 5 of the 268 cases was structural collapse so extensive as to preclude human survivability. In the remaining cases, considerable injury and fatality are observed despite the fact that these cases met the criterion of survivability.

To clarify the picture further, intercorrelations were derived between the primary impact variables, environmental damage, and injury severity. The correlations (Table 11), derived from contingency tables, are in nice agreement with common observations: both impact velocity and stopping distance are inversely related to angle of impact; stopping distance is directly related to impact velocity; environmental damage is directly related to velocity and angle of impact and inversely related to stopping distance. But, keeping objectives in mind, attention should be focused upon the last column of Table 11. None of the impact variables (velocity, angle, or stopping distance) correlated too high with injury

TABLE 10
RELATION OF OCCUPANT ENVIRONMENT DAMAGE TO INJURY SEVERITY

Pilot's Environment Condition	N	Mean Degree of Injury	Percent Fatal
Intact	110	2.37	1
Distorted	74	3.53	14
Partly Collapsed	79	4.91	27
Collapsed	5	8.40	80

TABLE 11
INTERCORRELATIONS OF THE ACCIDENT VARIABLES

Variable	2	3	4	5
1. Impact Velocity	-.33	.49	.21	.14
2. Angle of Impact		-.55	.41	.35
3. Stopping Distance			-.27	-.33
4. Pilot's Environment Damage				.47
5. Injury Severity				

severity. A moderate correlation was found between environmental damage and injury severity; but from a knowledge of environmental damage, this correlation enables one to predict or account for only 22 percent of the variation in injury. At the same time, this fact need not be interpreted to mean that structural collapse caused injury: occupants could have been thrown against collapsed structures.

DISCUSSION

A number of factors have been evaluated as to their role in determining injury severity. Tiedown failure can be a major determinant of injury, especially when impact conditions are severe. However, tiedown failure was observed in only 23 percent of the cases studied, and undoubtedly many of the injuries in these cases could have been attributed to other factors. One might argue in some cases that if crash forces were so great as to cause belts to fail, then they could also be sufficiently abrupt to account for the severe brain concussion or ruptured aorta often found with rapid decelerations, even under conditions where belts would be effective. But when impact variables were evaluated in this study, only a fraction of the cases could be classed as severe impacts (i. e., high angle, high velocity, short deceleration distance). There were still large numbers of cases for which injury severity was unaccounted.

An analysis was next made of the role of structural collapse in cases where no tiedown failure was observed. Here it was found that by a large margin injury and fatality were still in evidence despite the fact that structural collapse was not extensive. So what is causing these injuries if it is not abrupt deceleration, tiedown failure, or structural collapse?

The answer, it is felt, is flailing of the body against injury-producing structures within the occupant's environment. Now, it is true that the act of flailing cannot be objectively determined from postcrash data; it can only be inferred. But who will deny that flailing occurs? Studies of individual cases in which effort was made to determine whether contact had occurred between an object and a particular body area certainly support the above argument. The work of Swearingen et al (reference 7) is also relevant here. They have photographed the motions of the body during deceleration for 100 subjects restrained by a 2-inch seat belt. The obtained head clearance curve, when superimposed on an outline of a typical lightplane instrument panel, lends further support to the above conclusion. Their work also supports the conclusion that injury severity in modern lightplane crashes is largely a function of severity of head injury. Recent data (reference 2) demonstrate that 76 percent of the variation in injury severity can be attributed to severity of head injury. It should be obvious, then, that violent contact between the head and structures must be prevented through use of the shoulder harness, of the crash helmet, and of crash-safe design principles within the cockpit.

At the same time, there is still room for improvement in design, manufacture, and installation of components of the tiedown chain. Unfortunately, there was not enough pertinent data in this study to determine whether increased use of the shoulder harness would lead to an increase in the frequency of lumbar spine fractures. This inference, suggested by previous lightplane accident and Air Force studies (references 3, 4, and 6), is based on the premise that adequate restraint could contribute to lumbar spine injury insofar as it acts as a counterforce against which vertical forces are applied. If this is the price that has to be paid for protection against fatal head injuries, then even greater attention should be given to the incorporation of energy-absorbing features in seat design.

Knowledge of the precise ways in which seats and belts fail under dynamic loads is still limited. Even the specification of what dynamic loads to impose in controlled tests requires more information than can be derived from the gross accident summaries presented in this report. The seats themselves and the manner of belt anchorage vary widely in the aircraft included in the summaries. However, one tendency appears quite clearly. The rate at which seats tore free was higher for the more recent crashes and is now higher than the rate at which seat belts fail. According to the current Civil Aeronautics Regulations, the seat tiedown strength is 2,040 pounds (170 x 9 x 1.33). The loop strength of present seat belts is 3,000 pounds. In many cases belts are attached to the seat itself and with the human occupant undergoing horizontal deceleration, it should be expected that the seat might fail before the belt. With crash configurations where the principle direction of force is downward, the mass of the occupant is contributing to the failure of the seat, but very little to failure of the belt.

Results of the present study suggest the generalization that most lightplane crashes can be classified into one of two types: (a) The low-angle, high-speed, long-deceleration crash typified by the forced landing and in which tiedown effectiveness is of particular importance; and (b) the high-angle, moderate-speed, short-deceleration crash typical of the spin-stall accident and in which tiedown effectiveness loses some importance and the role of energy-absorbing forward structures must be emphasized. Besides design considerations, this generalization has obvious implications for pilot behavior and training. The first type is obviously much safer, whereas the second type is definitely to be avoided, if possible, since injury severity increases rapidly as a function of impact angle. But high-angle lightplane crashes can be survived if crash safety design principles are adopted as in the case of a comparatively recent model of an agricultural aircraft. In this model, structures are designed to absorb energy by progressive collapse and the cockpit is located as far aft in the fuselage as possible. Records to date on file at AvCIR contain not a single instance in which a fatal crash injury was incurred by any occupant of this aircraft when he was making proper use of shoulder harness, crash helmet, and seat belt.

Looking ahead, developments leading to increased aircraft performance are to be expected. There is no evidence yet that the majority of lightplane crashes are approaching any type of safety threshold. If the point should be reached, however, when death can be attributed to crash forces per se, then perhaps the day will arrive when the use of chutes or ejection seats will become indicated.

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